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Measurement of the $B^0 \to \bar{\Lambda} p \pi^-$ Branching Fraction and Study of the Decay Dynamics

The *BABAR* Collaboration

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Abstract

We present a measurement of the $B^0 \to \bar{\Lambda} p \pi^-$ branching fraction performed using the *BABAR* detector at the PEP-II asymmetric energy e^+e^- collider. Based on a 232 million $B\bar{B}$ pairs data sample we measure: $\mathcal{B}(B^0 \to \bar{\Lambda} p \pi^-) = [3.30 \pm 0.53 \text{ (stat.)} \pm 0.31 \text{ (syst.)}] \times 10^{-6}$. A measurement of the differential spectrum as a function of the di-baryon invariant mass $m(\Lambda p)$ is also presented; this shows a near-threshold enhancement similar to that observed in other baryonic B decays.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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The *BABAR* Collaboration,

B. Aubert, R. Barate, M. Bona, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

E. Grauges

Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain

A. Palano

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, I. Ofte, B. Stugu

University of Bergen, Institute of Physics, N-5007 Bergen, Norway

G. S. Abrams, M. Battaglia, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, M. S. Gill, Y. Groysman, R. G. Jacobsen, J. A. Kadyk, L. T. Kerth, Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

P. del Amo Sanchez, M. Barrett, K. E. Ford, A. J. Hart, T. J. Harrison, C. M. Hawkes, S. E. Morgan, A. T. Watson

University of Birmingham, Birmingham, B15 2TT, United Kingdom

T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, K. Peters, T. Schroeder, M. Steinke

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

J. T. Boyd, J. P. Burke, W. N. Cottingham, D. Walker

University of Bristol, Bristol BS8 1TL, United Kingdom

D. J. Asgeirsson, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna

University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

A. Khan, P. Kyberd, M. Saleem, D. J. Sherwood, L. Teodorescu

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, K. Yu Todyshev

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

D. S. Best, M. Bondioli, M. Bruinsma, M. Chao, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, E. Martin, R. K. Mommsen, W. Roethel, D. P. Stoker

University of California at Irvine, Irvine, California 92697, USA

S. Abachi, C. Buchanan

University of California at Los Angeles, Los Angeles, California 90024, USA

S. D. Foulkes, J. W. Gary, O. Long, B. C. Shen, K. Wang, L. Zhang
University of California at Riverside, Riverside, California 92521, USA

H. K. Hadavand, E. J. Hill, H. P. Paar, S. Rahatlou, V. Sharma
University of California at San Diego, La Jolla, California 92093, USA

J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, D. Kovalskyi, J. D. Richman
University of California at Santa Barbara, Santa Barbara, California 93106, USA

T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

J. Albert, E. Chen, A. Dvoretskii, F. Fang, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel
California Institute of Technology, Pasadena, California 91125, USA

G. Mancinelli, B. T. Meadows, K. Mishra, M. D. Sokoloff
University of Cincinnati, Cincinnati, Ohio 45221, USA

F. Blanc, P. C. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, M. Nagel, U. Nauenberg, A. Olivas, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang
University of Colorado, Boulder, Colorado 80309, USA

A. Chen, E. A. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, F. Winklmeier, Q. Zeng
Colorado State University, Fort Collins, Colorado 80523, USA

D. D. Altenburg, E. Feltresi, A. Hauke, H. Jasper, J. Merkel, A. Petzold, B. Spaan
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany

T. Brandt, V. Klose, H. M. Lacker, W. F. Mader, R. Nogowski, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann, A. Volk
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

D. Bernard, G. R. Bonneaud, E. Latour, Ch. Thiebaux, M. Verderi
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

P. J. Clark, W. Gradl, F. Muheim, S. Playfer, A. I. Robertson, Y. Xie
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

M. Andreotti, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, A. Petrella, L. Piemontese, E. Prencipe
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Pacetti, P. Patteri, I. M. Peruzzi,[1] M. Piccolo, M. Rama, A. Zallo
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

[1]Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

G. Brandenburg, K. S. Chaisanguanthum, M. Morii, J. Wu

Harvard University, Cambridge, Massachusetts 02138, USA

R. S. Dubitzky, J. Marks, S. Schenk, U. Uwer

Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

D. J. Bard, W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, R. L. Flack, J. A. Nash, M. B. Nikolich, W. Panduro Vazquez

Imperial College London, London, SW7 2AZ, United Kingdom

P. K. Behera, X. Chai, M. J. Charles, U. Mallik, N. T. Meyer, V. Ziegler

University of Iowa, Iowa City, Iowa 52242, USA

J. Cochran, H. B. Crawley, L. Dong, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin

Iowa State University, Ames, Iowa 50011-3160, USA

A. V. Gritsan

Johns Hopkins University, Baltimore, Maryland 21218, USA

A. G. Denig, M. Fritsch, G. Schott

Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany

N. Arnaud, M. Davier, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, S. Pruvot, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, W. F. Wang, G. Wormser

Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B.P. 34, F-91898 ORSAY Cedex, France

C. H. Cheng, D. J. Lange, D. M. Wright

Lawrence Livermore National Laboratory, Livermore, California 94550, USA

C. A. Chavez, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, D. J. Payne, K. C. Schofield, C. Touramanis

University of Liverpool, Liverpool L69 7ZE, United Kingdom

A. J. Bevan, F. Di Lodovico, W. Menges, R. Sacco

Queen Mary, University of London, E1 4NS, United Kingdom

G. Cowan, H. U. Flaecher, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, A. C. Wren

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

D. N. Brown, C. L. Davis

University of Louisville, Louisville, Kentucky 40292, USA

J. Allison, N. R. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, M. T. Naisbit, J. C. Williams, J. I. Yi

University of Manchester, Manchester M13 9PL, United Kingdom

C. Chen, W. D. Hulsbergen, A. Jawahery, C. K. Lae, D. A. Roberts, G. Simi

University of Maryland, College Park, Maryland 20742, USA

G. Blaylock, C. Dallapiccola, S. S. Hertzbach, X. Li, T. B. Moore, S. Saremi, H. Staengle

University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, G. Sciolla, S. J. Sekula, M. Spitznagel, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

H. Kim, S. E. Mclachlin, P. M. Patel, S. H. Robertson

McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo

Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA

S. Brunet, D. Côté, M. Simard, P. Taras, F. B. Viaud

Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

H. Nicholson

Mount Holyoke College, South Hadley, Massachusetts 01075, USA

N. Cavallo,[2] G. De Nardo, F. Fabozzi,[3] C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. A. Baak, G. Raven, H. L. Snoek

NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco

University of Notre Dame, Notre Dame, Indiana 46556, USA

T. Allmendinger, G. Benelli, L. A. Corwin, K. K. Gan, K. Honscheid, D. Hufnagel, P. D. Jackson, H. Kagan, R. Kass, A. M. Rahimi, J. J. Regensburger, R. Ter-Antonyan, Q. K. Wong

Ohio State University, Columbus, Ohio 43210, USA

N. L. Blount, J. Brau, R. Frey, O. Igonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence

University of Oregon, Eugene, Oregon 97403, USA

[2]Also with Università della Basilicata, Potenza, Italy

[3]Also with Università della Basilicata, Potenza, Italy

A. Gaz, M. Margoni, M. Morandin, A. Pompili, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, L. Del Buono, Ch. de la Vaissière, O. Hamon, B. L. Hartfiel, M. J. J. John, Ph. Leruste, J. Malclès, J. Ocariz, L. Roos, G. Therin
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France

L. Gladney, J. Panetta
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

M. Biasini, R. Covarelli, E. Manoni
Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

C. Angelini, G. Batignani, S. Bettarini, F. Bucci, G. Calderini, M. Carpinelli, R. Cenci, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. A. Mazur, M. Morganti, N. Neri, E. Paoloni, G. Rizzo, J. J. Walsh
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy

M. Haire, D. Judd, D. E. Wagoner
Prairie View A&M University, Prairie View, Texas 77446, USA

J. Biesiada, N. Danielson, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov
Princeton University, Princeton, New Jersey 08544, USA

F. Bellini, G. Cavoto, A. D'Orazio, D. del Re, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Safai Tehrani, C. Voena
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

M. Ebert, H. Schröder, R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye, N. De Groot, B. Franek, E. O. Olaiya, F. F. Wilson
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. Vasseur, Ch. Yèche, M. Zito
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

X. R. Chen, H. Liu, W. Park, M. V. Purohit, J. R. Wilson
University of South Carolina, Columbia, South Carolina 29208, USA

M. T. Allen, D. Aston, R. Bartoldus, P. Bechtle, N. Berger, R. Claus, J. P. Coleman, M. R. Convery, M. Cristinziani, J. C. Dingfelder, J. Dorfan, G. P. Dubois-Felsmann, D. Dujmic, W. Dunwoodie, R. C. Field, T. Glanzman, S. J. Gowdy, M. T. Graham, P. Grenier,[4] V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, D. W. G. S. Leith, S. Li, S. Luitz, V. Luth, H. L. Lynch, D. B. MacFarlane, H. Marsiske, R. Messner, D. R. Muller, C. P. O'Grady, V. E. Ozcan, A. Perazzo, M. Perl, T. Pulliam, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, J. Stelzer, D. Su, M. K. Sullivan, K. Suzuki, S. K. Swain, J. M. Thompson, J. Va'vra, N. van

[4]Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France

Bakel, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young
Stanford Linear Accelerator Center, Stanford, California 94309, USA

P. R. Burchat, A. J. Edwards, S. A. Majewski, B. A. Petersen, C. Roat, L. Wilden
Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain
State University of New York, Albany, New York 12222, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier
University of Tennessee, Knoxville, Tennessee 37996, USA

R. Eckmann, J. L. Ritchie, A. Satpathy, C. J. Schilling, R. F. Schwitters
University of Texas at Austin, Austin, Texas 78712, USA

J. M. Izen, X. C. Lou, S. Ye
University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi, F. Gallo, D. Gamba
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

M. Bomben, L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, L. Lanceri, L. Vitale
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal
IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

Sw. Banerjee, B. Bhuyan, C. M. Brown, D. Fortin, K. Hamano, R. Kowalewski, I. M. Nugent, J. M. Roney, R. J. Sobie
University of Victoria, Victoria, British Columbia, Canada V8W 3P6

J. J. Back, P. F. Harrison, T. E. Latham, G. B. Mohanty, M. Pappagallo
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, B. Cheng, S. Dasu, M. Datta, K. T. Flood, J. J. Hollar, P. E. Kutter, B. Mellado, A. Mihalyi, Y. Pan, M. Pierini, R. Prepost, S. L. Wu, Z. Yu
University of Wisconsin, Madison, Wisconsin 53706, USA

H. Neal
Yale University, New Haven, Connecticut 06511, USA

1 INTRODUCTION

Observations of charmless three-body baryonic B decays have been reported recently by both the *BABAR* and Belle collaborations [1, 2, 3]. A common feature of these decay modes is the peaking of the baryon-antibaryon mass spectrum toward threshold. This feature has stimulated considerable interest among theorists as a key element in the explanation of the unexpectedly high branching fractions for these decays [4, 5]. We report a measurement of the branching fraction for B^0 decay to the $\bar{\Lambda}p\pi^-$ final state [5]. In the Standard Model this decay proceeds through tree level $b \to u$ and penguin $b \to s$ amplitudes. It is of interest to study the structure of the decay amplitude in the Dalitz plane and to test the afore-mentioned theoretical expectations. This channel may also be used to search for direct CP violation, and with the Λ hyperon in the final state, its spin self-analyzing weak decay to $p\ \pi$, may be used, with increased statistics, to study the chirality structure of weak $b \to s$ transitions [6] and to probe T violation [4, 7].

2 THE *BABAR* DETECTOR AND DATASET

The data sample consists of 232 million $B\bar{B}$ pairs corresponding to an integrated luminosity of 210.3 fb^{-1}, collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector. The detector is described in detail elsewhere [8]. Charged particle trajectories are measured in a tracking system consisting of a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer central drift chamber (DCH), both operating in a 1.5-T axial magnetic field. A ring-imaging Cherenkov detector (DIRC) is used for charged-particle identification. A CsI(Tl) electromagnetic calorimeter (EMC) is used to detect and identify photons and electrons, while muons are identified in the instrumented flux return of the magnet (IFR). A *BABAR* detector Monte Carlo simulation based on GEANT4 [9] is used to optimize selection criteria and determine selection efficiencies.

3 EVENT SELECTION

We reconstruct Λ candidates in the $\Lambda \to p\pi$ decay mode as combinations of oppositely-charged tracks, assigned the proton and pion mass hypotheses, and fit to a common vertex. A fit to the invariant mass distribution of reconstructed candidates with a triple Gaussian gives RMS widths of $0.7\,\mathrm{MeV}/c^2$, $1.3\,\mathrm{MeV}/c^2$ and $4.0\,\mathrm{MeV}/c^2$ for the narrow, intermediate and wide Gaussians respectively, with an average value of $1.8\,\mathrm{MeV}/c^2$. Combinations with an invariant mass in the range $1.111 - 1.121\,\mathrm{GeV}/c^2$ are refit with a mass constraint to the nominal Λ mass [10], and combined with two additional tracks with opposite charges, each with momentum transverse to the beam greater than $100\,\mathrm{MeV}/c$.

Measurements of the average energy loss ($\mathrm{d}E/\mathrm{d}x$) in the tracking devices, angle of the Cherenkov cone in the DIRC, and energy releases in the EMC and IFR are combined to give a likelihood estimator for a track to be consistent with a given particle hypothesis. Tracks with likelihood ratios satisfying the very loose particle identification (PID) criterion $L_p/L_K > 1/3$ and $L_p/L_\pi > 1$ are assumed to be protons. In addition, the pion that originates from the B decay vertex must satisfy a loose PID criterion $L_\pi/L_K > 0.22$ and $L_\pi/L_p > 0.02$. A Kalman fit [11] to the full decay sequence is used to reconstruct the B vertex; only candidates with a fit probability $P_{\mathrm{vtx}} > 10^{-6}$ are considered.

[5] Inclusion of the charge conjugate mode is implied.

The primary background to the reconstructed decay channel arises from light quark continuum events $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$), which are characterized by collimation of final state particles with respect to the quark direction, in contrast to the more spherical $B\bar{B}$ events. Exploiting these different topologies we can increase the signal significance using topological variables computed from the center-of-mass (CM) momenta of all reconstructed charged and neutral particles in the event. For each event we linearly combine the sphericity, the angle between the B thrust axis and detector longitudinal axis, and the zeroth and second order Legendre moments into a Fisher discriminant ($\mathcal{F}$) [12], whose coefficients are chosen to optimize the separation of signal and continuum background Monte Carlo samples. After optimization of the selection with respect to the simultaneous variation of all the selection criteria, we obtain that the Fisher requirement retains 71.2% of the candidates from the signal Monte Carlo sample and only 6.4% from the continuum background Monte Carlo.

To further reduce combinatoric background we take advantage of the long mean lifetime of Λ particles and require that the separation of the Λ and B^0 vertices divided by its measurement error, computed on a per candidate basis by the fit procedure, exceeds 35. This criterion was optimized on Monte Carlo events and is effective in rejecting 42% of combinatorial background that survived all other cuts, while retaining 90% of signal candidates. The only sizable B background is from the process $B^0 \to \bar{\Lambda}_c{}^- (\to \bar{\Lambda}\pi^-)\, p$, and we reject this with a veto on candidates with an invariant mass $m(\Lambda\pi)$, within $20\,\mathrm{MeV}/c^2$, approximately 5 standard deviations, of the nominal Λ_c mass [10].

The kinematic constraints on B mesons produced at the $\Upsilon(4S)$ allow further background discrimination using the variables m_{ES} and ΔE. We define $m_{\mathrm{ES}} = \sqrt{\left(\frac{s}{2} + \vec{p}_i \cdot \vec{p}_B\right)^2 / E_i^2 - \vec{p}_B{}^2}$ where $(E_i, \vec{p}_i)$ is the four momentum of the initial e^+e^- system and $\vec{p}_B$ the momentum of the reconstructed B candidate, both measured in the laboratory frame, and s is the square of the total available energy in the $\Upsilon(4S)$ center of mass frame. We have $\Delta E = E_B^* - \frac{\sqrt{s}}{2}$ where E_B^* is the B energy in the $\Upsilon(4S)$ center of mass frame. Candidates satisfying $|\Delta E| < 200\,\mathrm{MeV}$ and $5.2 < m_{\mathrm{ES}} < 5.29\,\mathrm{GeV}/c^2$ are used in the maximum likelihood fitting process.

4 BRANCHING FRACTION

We perform the measurement using a maximum-likelihood fit on m_{ES}-ΔE observables of reconstructed B candidates. The ${}_s\mathcal{P}$lot technique [14] , is then used to determine the $m(\bar{\Lambda}p)$ distribution of reconstructed candidates and, once the correction for the nonuniform reconstruction efficiency is applied, measure the $m(\bar{\Lambda}p)$-dependent differential rate together with the total branching fraction.

We consider as signal events only reconstructed B meson candidates whose daughters are correctly assigned in the decay chain. By self-cross-feed, we refer to candidates reconstructed as signal events in which one or more particles are not correctly assigned in the decay chain. Examples of such misreconstruction include events in which a proton from the other B meson are associated to the signal B, and events where the protons from the signal B and Λ decays are interchanged. We define the total PDF in the ΔE-m_{ES} plane as the sum of signal, self-cross-feed, and background components:

$$\mathcal{L} = \frac{1}{N!} e^{-(N_{\mathrm{S}}+N_{\mathrm{B}}+N_{\mathrm{S}} f_{\mathrm{scf}})} \prod_{\alpha=1}^{N} \left[N_{\mathrm{S}} \mathcal{P}_{\mathrm{S},\alpha} + N_{\mathrm{B}} \mathcal{P}_{\mathrm{B},\alpha} + N_{\mathrm{S}} f_{\mathrm{scf}} \mathcal{P}_{\mathrm{scf},\alpha} \right] \tag{1}$$

where the product is over the N fitted events with N_{S} and N_{B} representing the number of signal and background candidates and f_{scf} representing the self-cross-feed fraction. The three $\mathcal{P}$ functions are taken as products of 1-dimensional ΔE and m_{ES} PDF's. We are justified in this simplification

by the small correlation between these two variables in our Monte Carlo sample, measured as -7.4% for signal, and -0.5% for background. The $m_{\rm ES}$ PDF is taken as a double Gaussian for the signal and a threshold function [13] for the background. The ΔE PDF is taken as a double Gaussian for the signal and a first order polynomial for the background. Finally, the self-cross-feed contribution shows a peaking component that is modeled as the product of a double Gaussian in ΔE and a single Gaussian in $m_{\rm ES}$. The self cross-feed fraction $f_{\rm scf} = 0.59\%$, and the other parameters that enter the definition of its contribution to the PDF have been determined from a Monte Carlo sample of signal events.

We vary the means of the narrow ΔE and $m_{\rm ES}$ signal Gaussians, the coefficient in the exponential of the Argus function, the linear coefficient of the ΔE background distribution, and the event yields $N_{\rm S}$ and $N_{\rm B}$. The means of the wide Gaussians are determined by applying Monte Carlo determined offsets to the mean of the narrow ones, such that only an overall shift of the fixed PDF shape is allowed.

Once the maximum likelihood fit provides the best estimates of the PDF parameters, we use the ${}_s\mathcal{P}$lot technique [14] to reconstruct the efficiency-corrected $m(\bar{\Lambda}p)$ distribution and measure the branching fraction. The PDF is used to compute the s-weight for the n-th component of event e as:

$$ {}_s\mathcal{P}_n(y_e) = \frac{\sum_{j=1}^{n_{\rm c}} \mathbf{V}_{nj}\mathcal{P}_j(y_e)}{\sum_{k=1}^{n_{\rm c}} N_k\mathcal{P}_k(y_e)} \tag{2} $$

where the indices n, j and k run over the $n_{\rm c} = 2$ signal and background components whose distributions, as functions of $y_e = (m_{{\rm ES},e}, \Delta E_e)$, are identified with the $\mathcal{P}_j(y_e)$ symbol. $\mathbf{V}_{nj}$ is the covariance matrix of the event yields as measured from the fit of the PDF to the data sample. An important property of the ${}_s\mathcal{P}$lot is that the sum of s-weights for the signal or background component equals the corresponding number of fitted signal or background candidates. Thus the ${}_s\mathcal{P}$lot is a good estimator of the $m(\bar{\Lambda}p)$ distribution, and preserves the total signal yield, as determined by the maximum likelihood fit. To retrieve the efficiency-corrected number of events in given $m(\bar{\Lambda}p)$ bin J we use the s-weight sum:

$$ N_J = \sum_{e\in J} \frac{{}_s\mathcal{P}_n(y_e)}{\varepsilon(x_e)}, \tag{3} $$

where $\varepsilon(x_e)$ is the per-event overall efficiency. The reconstruction efficiency depends on the position of the candidate on the square Dalitz plane $x_e = (m_{\Lambda p}, \cos(\theta_{\rm H}))$, $\theta_{\rm H}$ being the helicity angle of the pion in the $\bar{\Lambda}p$ rest frame, and has been measured on a 10×10 grid over the square Dalitz plane, using fully reconstructed signal Monte Carlo events. The error $\sigma\left[N_J\right]$ in N_J is given by:

$$ \sigma^2\left[N_J\right] = \sum_{e\in J} \left(\frac{{}_s\mathcal{P}_n(y_e)}{\varepsilon(x_e)}\right)^2. \tag{4} $$

An estimate of the efficiency-corrected number of events in the sample is given by the sum of the efficiency-corrected s-weights or

$$ N = \sum_J N_J, \tag{5} $$

and the total branching fractions is obtained from

$$ \mathcal{B}\left(B \to \Lambda p\pi\right) = \frac{N}{N_{B\bar{B}} \cdot \mathcal{B}\left(\Lambda \to p\pi\right)}. \tag{6} $$

Table 1: Systematic errors on the BF measurement.

	source	error
Overall	$B\bar{B}$ counting	1.1%
	$B^0\bar{B}^0/B\bar{B}$ fraction	1.4%
	Tracking efficiency	3.9%
	PID efficiency	1.4%
	MC statistics	2.0%
	$\Lambda \to p\pi$ branching fraction	0.8%
Event Selection	Event shape cut efficiency	2.4%
	Fit probability cut efficiency	5.0%
	Λ flight length cut efficiency	2.8%
	Λ mass cut efficiency	2.4%
	Λ_c veto cut	0.5%
Fit Procedure	Likelihood parameters	3.9%
	ΔE resolution	1.7%
	Self cross-feed fraction	0.8%
	${}_s\mathcal{P}$lot bias correction	0.6%
Total		9.4%

Using fully reconstructed signal Monte Carlo events, we have checked that this procedure provides a measurement of the $m(\bar{\Lambda}p)$ distribution and total branching fraction with negligible biases and accurate errors.

5 SYSTEMATIC ERRORS

Systematic errors are listed in Table I and classified as overall uncertainties, uncertainties associated with event selection, and uncertainties associated with fitting the signal event distribution. Tracking efficiency uncertainty dominates the first category with a contribution of 3.9%. Particle identification systematic errors were evaluated by studying data versus Monte Carlo agreement of identification efficiency on protons from a pure sample of $\Lambda \to p\pi$ decays and pions from $K^0_S \to \pi\pi$ decays. The finite signal Monte Carlo sample available to measure the reconstruction efficiency over the Dalitz plane, results in an additional 2.0% contribution to the systematic error. The uncertainty in the determination of the number of $B\bar{B}$ pairs in the data sample accounts for a 1.1% systematic, while the assumption of a 50% ratio of $B^0\bar{B}^0$ to $B\bar{B}$ at the $\Upsilon(4S)$ gives an additional 1.4% contribution, computed as the difference with respect to the current measured value $49.3 \pm 0.8\%$ [10].

Event selection systematic errors associated with the determination of the efficiencies of the Fisher-discriminant event shape cut and the vertex fit-probability cut, have been evaluated comparing data and Monte Carlo selection efficiencies of a sample of $B^0 \to J/\psi K^0_S$ candidates. In addition, we use an inclusive sample of $\Lambda \to p\pi$ candidates to estimate systematic errors associated with the determination of efficiencies of flight length-significance cut and Λ-mass requirement.

The application of the requirement on the reconstructed $m(\Lambda\pi)$ invariant mass to veto $B^0 \to \bar{\Lambda}_c p$ background has two associated systematic effects. The first causes an approximate 0.2% increase in

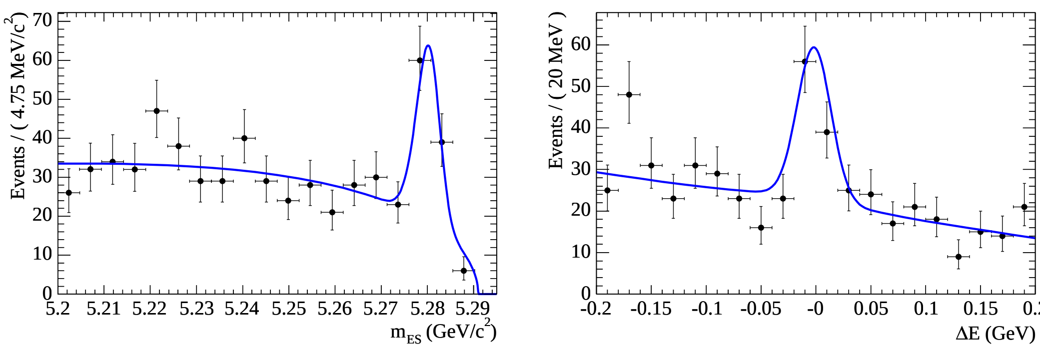

Figure 1: Left plot: $m_{\rm ES}$ distribution of candidates with $|\Delta E| < 27\,\mathrm{MeV}$. Right plot: ΔE distribution of candidates with $m_{\rm ES} > 5.274\,\mathrm{GeV}/c^2$. Superimposed are projections of the 2-dimensional fit PDF onto the respective axes.

the branching fraction due to the residual Λ_c component that survives the cut. The second causes an approximate 0.5% reduction of the branching fraction due to the reduced Dalitz-plot space. We take the larger of the two as the systematic error associated with the Λ_c veto cut.

We vary parameters that are kept fixed in the likelihood fit by their statistical errors, as measured on the signal MC sample fit, and measure the variation of the ${}_s\mathcal{P}$lot fitted result. The changes associated to the parameters that enter the definition of the signal PDF are conservatively considered as fully correlated and added linearly to give a signal PDF systematic error of 3.2%, where the uncertainty on signal $m_{\rm ES}$ fixed parameters accounts for a 1.9% contribution and the uncertainty on signal ΔE fixed parameters for a 1.3% contribution. The same procedure is applied to the parameters that enter the background PDF definition, with errors determined on luminosity-weighted background MC samples, giving an additional 2.2% systematic error. Finally, we combine in quadrature the two errors and obtain a 3.9% systematic error associated with uncertainties on the shape of signal and background PDF models. The comparison of $B \to J/\psi K^0_S$ data and Monte Carlo samples reveals that the width of the ΔE Gaussian in the signal PDF can be underestimated in the Monte Carlo by up to 5%, and this translates to an additional 1.7% systematic error associated with the uncertainty in the ΔE resolution.

We estimate possible biases associated with the determination of yields with the ${}_s\mathcal{P}$lot technique, using a collection of Monte Carlo experiments in which signal candidates, generated and reconstructed with a complete detector simulation, have been mixed with background candidates, choosing numbers of signal and background candidates similar to those expected on the data sample under study. Biases have been found within the statistical error in their measurement, and we estimate a 0.6% systematic uncertainty associated with the ${}_s\mathcal{P}$lot fitting technique.

6 RESULTS

We select a total of 4261 candidates in the region $|\Delta E| < 200\,\mathrm{MeV}$, $m_{\rm ES} > 5.2\,\mathrm{GeV}/c^2$, $|m(\Lambda\pi) - m(\Lambda_c)| > 20\,\mathrm{MeV}/c^2$ in the $210.3\,\mathrm{fb}^{-1}$ data sample considered. Table II contains the fitted values of the 2-dimensional $m_{\rm ES}$-ΔE PDF parameters, while Fig. 1 shows projections of the 2-dimensional PDF on the $m_{\rm ES}$ and ΔE axes. Figure 2 shows the efficiency-corrected signal ${}_s\mathcal{P}$lot distribution of candidates as a function of the $m(\bar{\Lambda}p)$ coordinate; this reveals a near-threshold enhancement

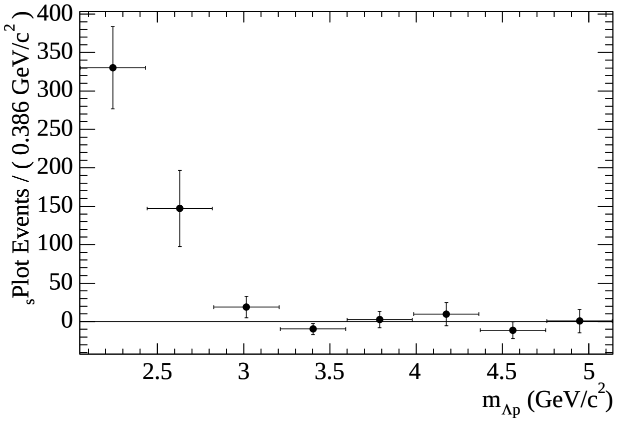

Figure 2: ${}_s\mathcal{P}$lot of the $m(\Lambda p)$ event distribution with efficiency corrections applied.

Table 2: Likelihood fit result. N_S and N_B are the number of fitted signal and background candidates respectively. $\mu\,(\Delta E)$ is the mean value for the narrow Gaussian of the ΔE signal PDF component, while $c_1\,(\Delta E)$ is the slope of the linear ΔE background PDF. $\mu\,(m_{\rm ES})$ is the mean value for the Gaussian of the $m_{\rm ES}$ signal PDF, and $c_{\rm Argus}\,(m_{\rm ES})$ is the coefficient at the exponent of the background $m_{\rm ES}$ Argus function as given in [13]. Reported errors are statistical only.

Parameter	Value
$N_{\rm S}$	$73.7^{+12.0}_{-11.2}$
$N_{\rm B}$	4187 ± 66
$\mu\,(\Delta E)$	$-1.71 \pm 3.10\,{\rm MeV}$
$c_1\,(\Delta E)$	-3.71 ± 0.25
$\mu\,(m_{\rm ES})$	$5.2808 \pm 0.0004\,{\rm GeV}/c^2$
$c_{\rm Argus}\,(m_{\rm ES})$	-15.1 ± 1.7

similar to that observed in other baryonic B decays. Summing the efficiency-corrected ${}_s\mathcal{P}$lot bins, we obtain a yield of 488 ± 79 signal events, where the error is statistical. Using Equation 6 we measure the branching fraction:

$$\mathcal{B}(B^0 \to \bar{\Lambda} p \pi^-) = [3.30 \pm 0.53\ ({\rm stat.}) \pm 0.31\ ({\rm syst.})] \times 10^{-6}.$$

This measurement, which is compatible with a previous measurement by the Belle collaboration[2], confirms the peaking of the baryon-antibaryon mass spectrum toward threshold, a feature that plays a key role in the explanation of the higher branching fraction of three-body baryonic B decays with respect to two body ones.

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The ARGUS function is defined as:

$$\mathrm{Argus}\,(m; m_0, c) = B\frac{m}{m_0}\left(1-\frac{m^2}{m_0^2}\right)^{1/2}\exp\left[c\left(1-\frac{m^2}{m_0^2}\right)\right]$$

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